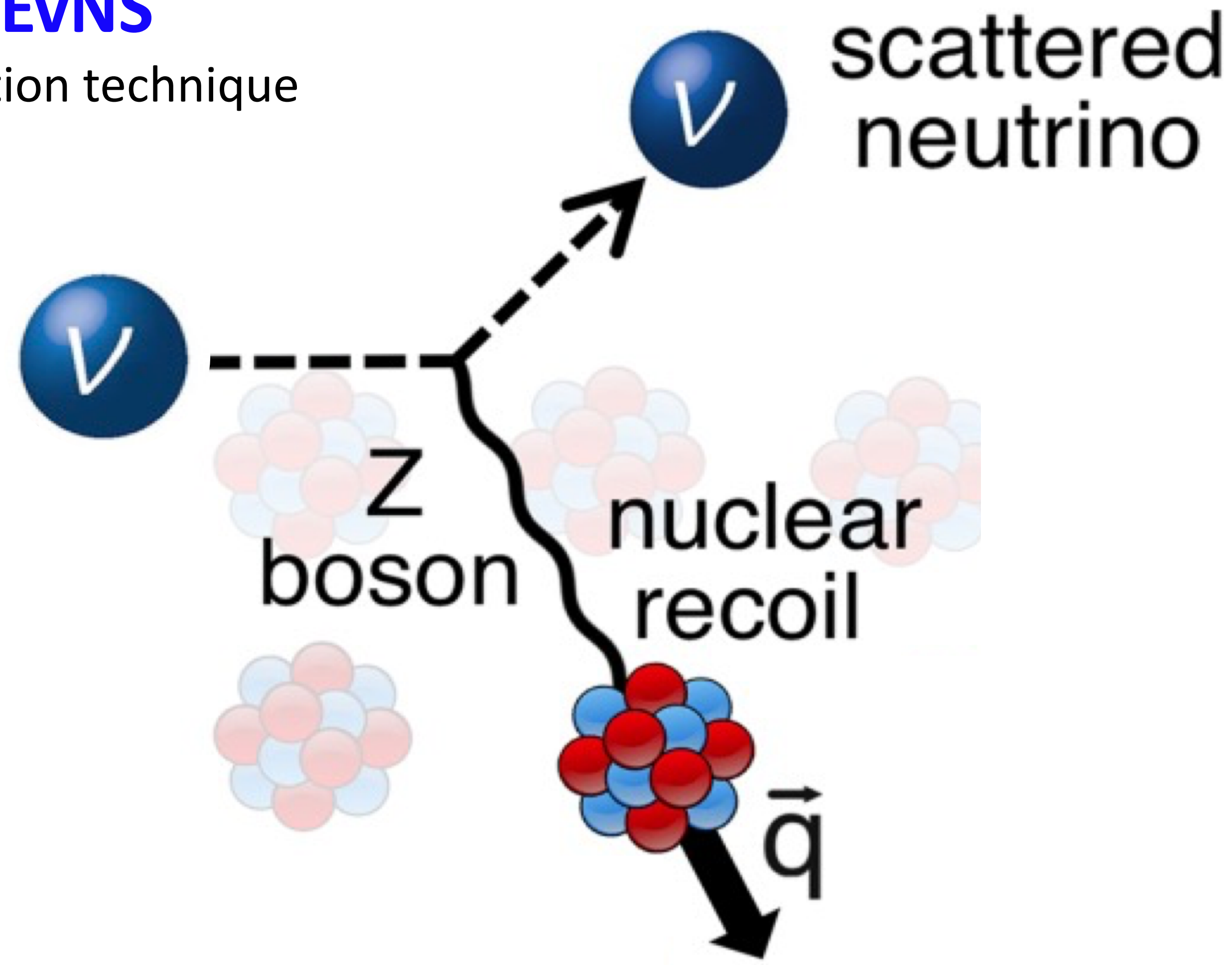
Experimental study of CEvNS

A brief review of experiments and detection technique

Dmitry Akimov, NRNU MEPhI

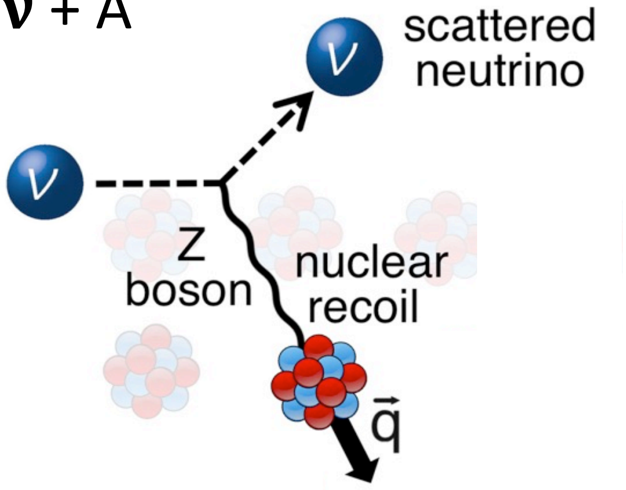


Icppa2024 - The 7th international conference on particle physics and astrophysics,
22 - 25 October 2024, Moscow

CEνNS is Coherent Elastic Neutrino-Nucleus Scattering

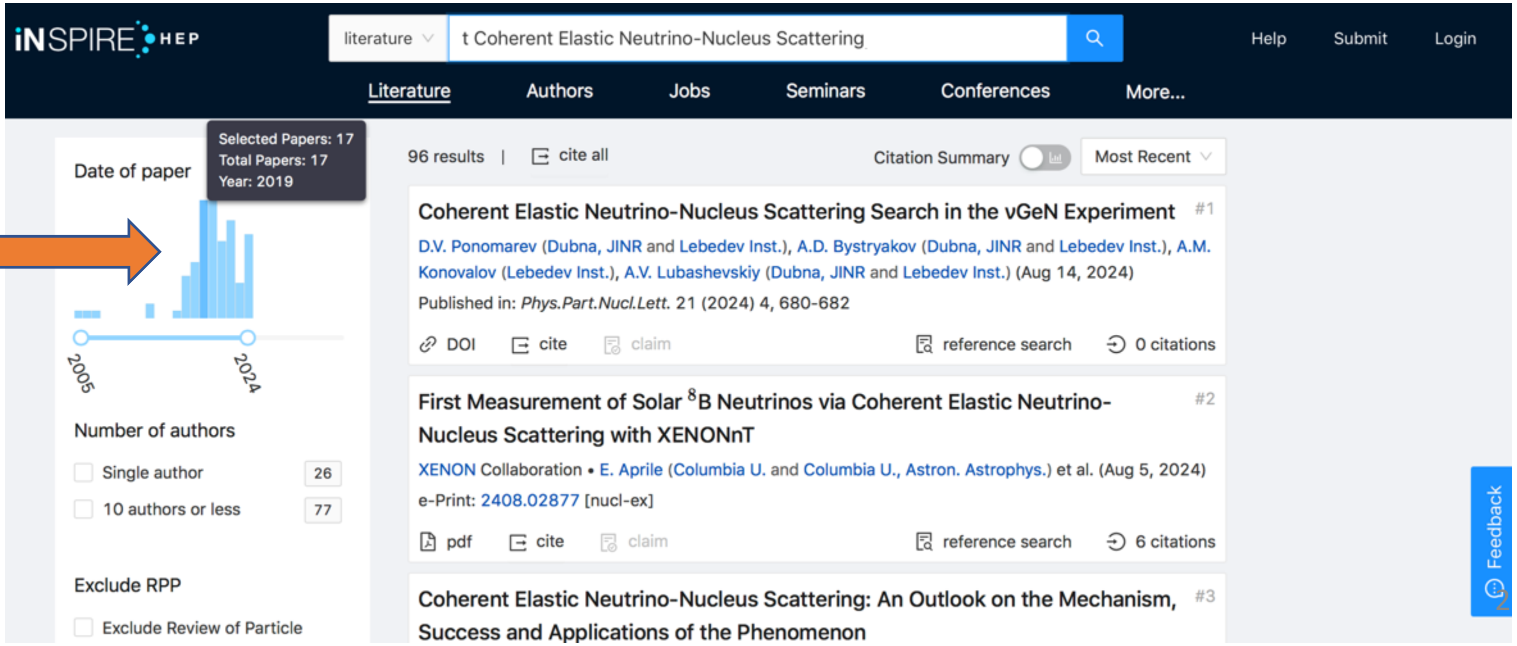
$\nu + A \Rightarrow \nu + A$

It was predicted theoretically **50 years ago** by:
D.Z. Freedman, Phys. Rev. D 9 (1974) 1389. **USA**
&
Kopeliovich V B, Frankfurt L L JETP Lett. 19 145 (1974); Pis'ma Zh. Eksp. Teor. Fiz. 19, 236 (1974). **USSR**
shortly after the discovery of a neutral current in neutrino interactions in the Gargamelle experiment at CERN. *Phys. Lett. B* 46, 138–140 (1973).



Observed only in 2017 by the COHERENT collaboration: Science, Vol. 357,15 Sep. 2017, p. 1123

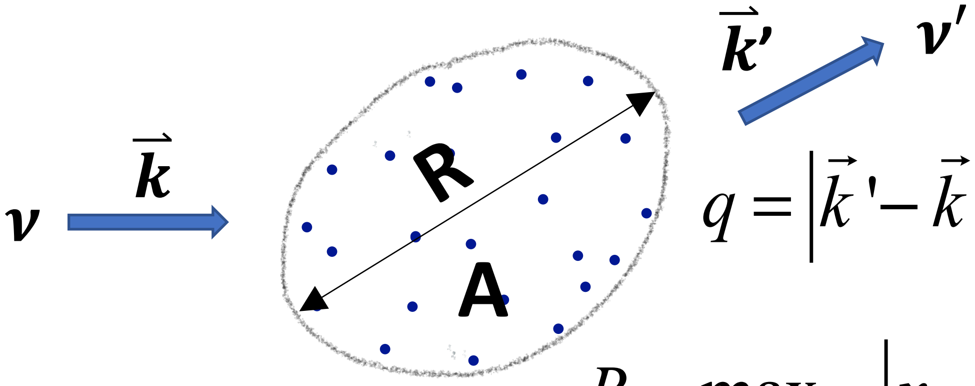
The intense study of CEνNSs started in 2017



What is coherent scattering?

Explanation given by Freedman D Z, Schramm D N, Tubbs D L *Ann. Rev. Nucl. Sci.* **27** (1977) 167

Consider a system composed from A scatter centers



$$q = \left|\vec{k}' - \vec{k}\right|$$

$$R = \max_{i,j} \left|x_i - x_j\right|$$

$f_j(\vec{k}',\vec{k})$ - scatter amplitude on each center

$$F(\vec{k}',\vec{k}) = \sum_{j=1}^{A} f_j(\vec{k}',\vec{k}) e^{i(\vec{k}'-\vec{k})\vec{x}_j}$$

if $qR \gtrsim 1$, scattering amplitudes cancel each other

if $qR << 1$, $f_j(\vec{k}',\vec{k})$ are added together, and $\sigma \sim A^2 \left|\bar{f}(\vec{k}'-\vec{k})\right|^2$

where $\bar{f}(\vec{k}'-\vec{k})$ is scatter amplitude averaged over the system

For the heavy nuclei, the condition qR <<1 is satisfied for **all** scattering angles at $E_\nu \lesssim$ several MeV

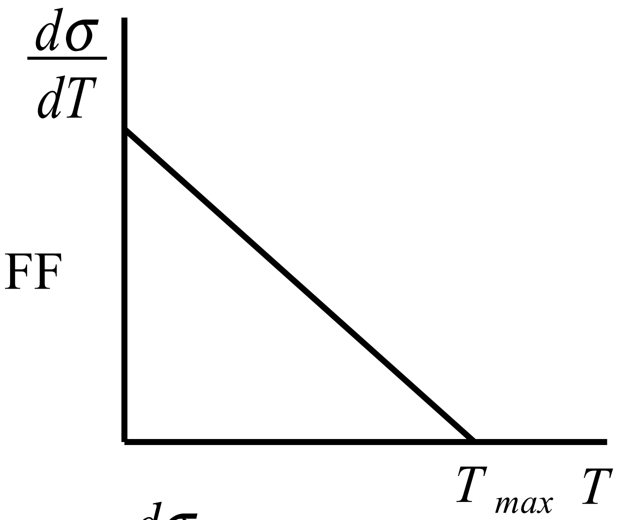
CEvNS cross-section

For the simplified case (even-even nuclei and $T \ll E_\nu$):

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} M Q_W^2 \left(1 - \frac{MT}{2E_\nu^2}\right) F_{\mathrm{nucl}}^2(Q^2)$$

where T – nucl. recoil energy, F – nuclear FF

$F=1$ for $qR \ll 1$, **but** $F < 1$ for $qR \lesssim 1$



$Q_W = [Z(1-4\sin^2\theta_W) - N]$ – weak nucl. charge $\sin^2\Theta_W \sim 0.25$ $\Longrightarrow \approx N$ $\frac{d\sigma}{dT} \sim N^2$.

Z – number of protons

N – number of neutrons

total $\sigma \approx 0.4 \cdot 10^{-44} N^2 (E_\nu)^2 \ \mathrm{cm}^2$

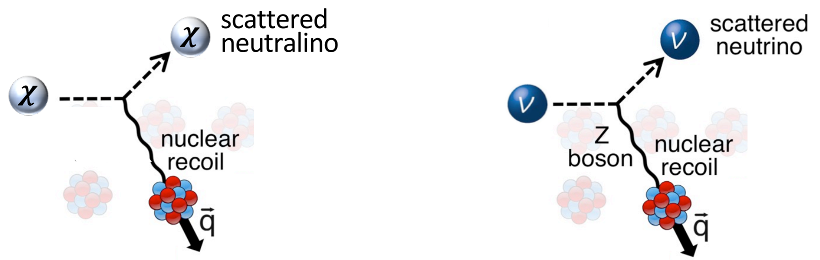
The ONLY signature of CEvNS is a nuclear recoil (NR) with energy of keV-scale for NPP reactor and 10s-keV-scale for πDAR

Detection technique of CEvNS is similar to that for WIMPs!

Both processes produce nuclear recoils (NR)

Both processes are rare ones!

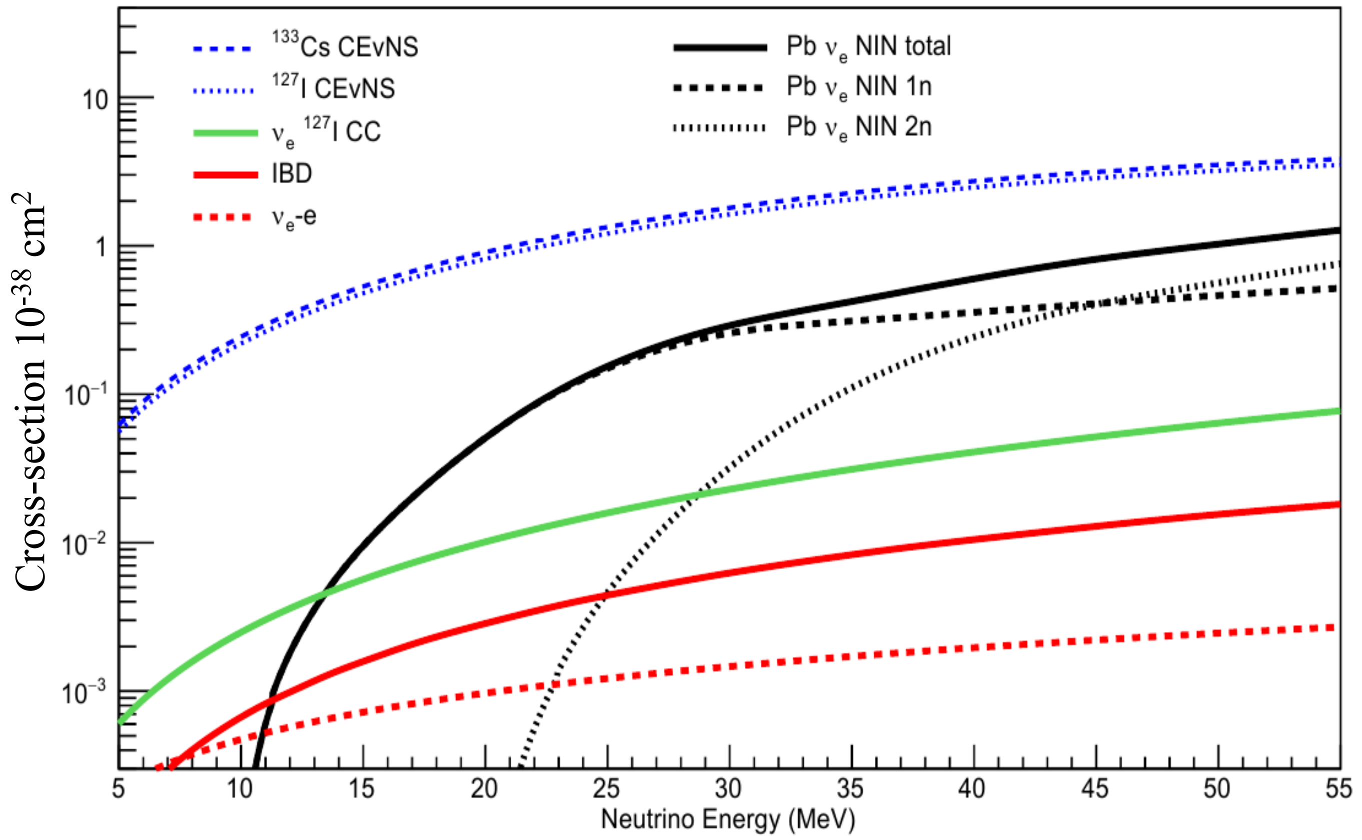
WIMP particle **Neutrino**



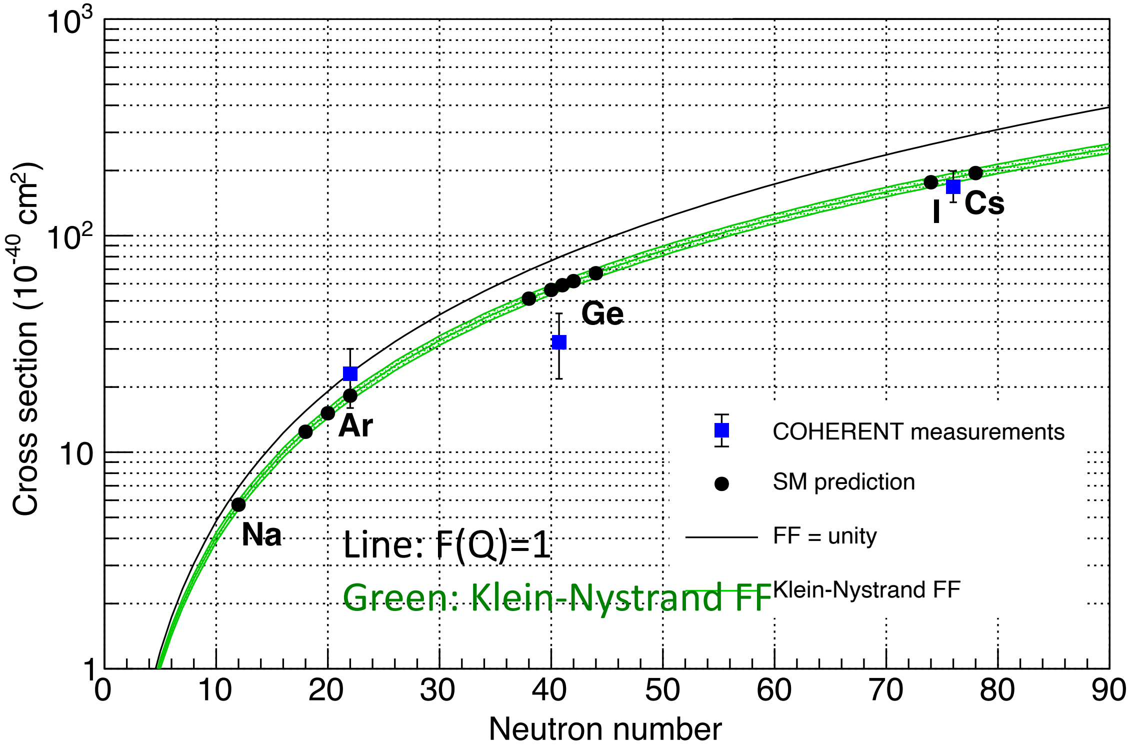
10-s keV **Reactor: keV** **πDAR: 10-s keV**

CEvNS cross-section

Dependence of the cross-section from ν energy



Dependence of the cross-section from neutron number



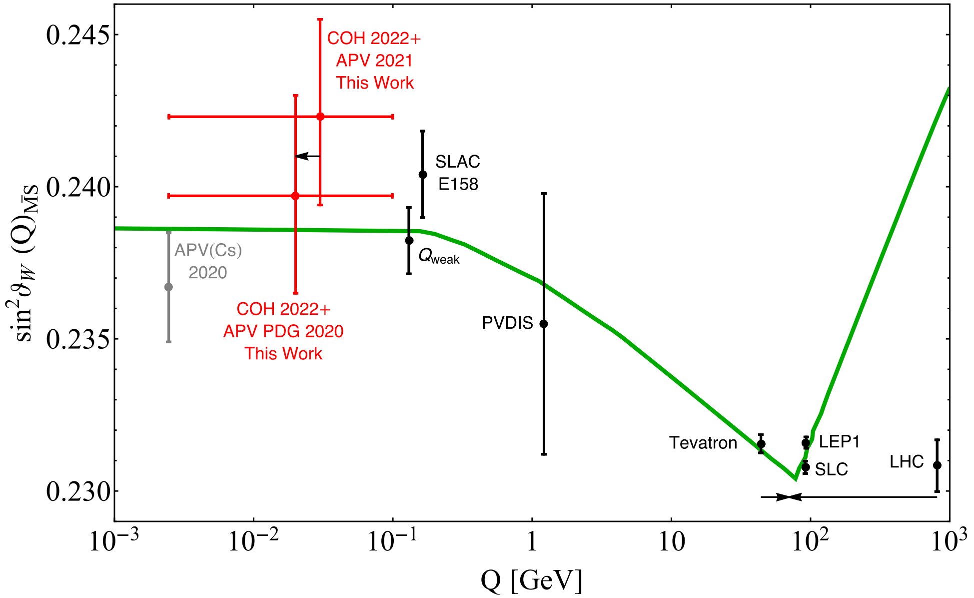
For heavy nuclei (Cs, I, Xe):

$\langle\sigma\rangle \sim 10^{-40}$ cm^2 (averaged for the reactor antineutrinos: 0 – ~10 MeV)

$\langle\sigma\rangle \sim 10^{-38}$ cm^2 (averaged for the "Pion-decay-at-rest" neutrinos: 0 – ~50 MeV)

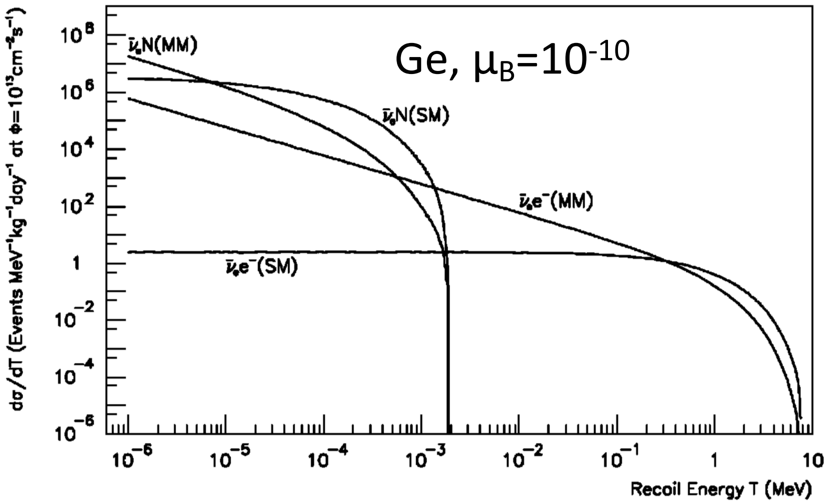
Motivation of CEvNS experiments

Physics, Standard Model

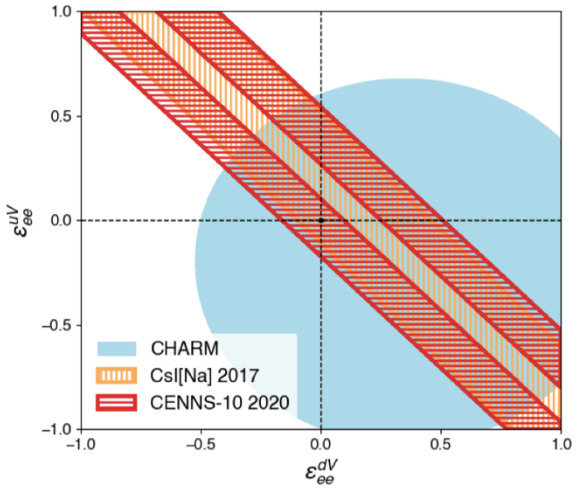


"Non-standard" physics; beyond SM:

ν magnetic moment



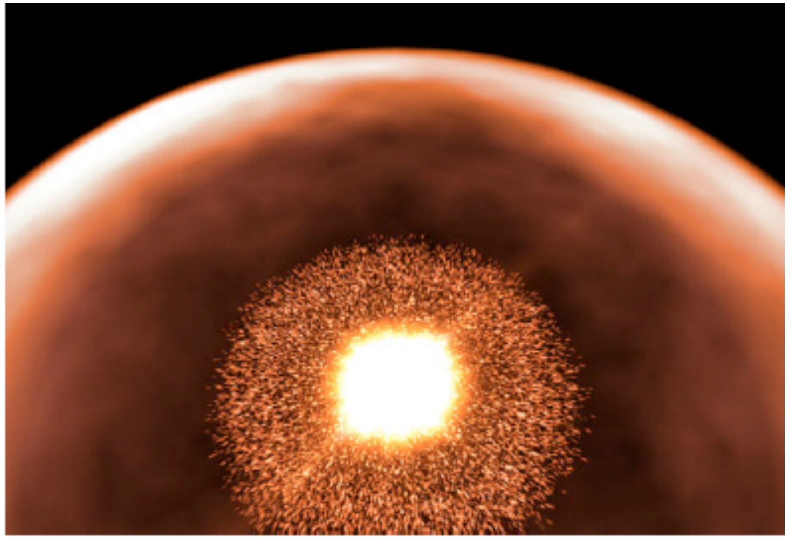
ν-quark interaction



Knowledge on the precise CEvNS cross-section is very important in astrophysics.

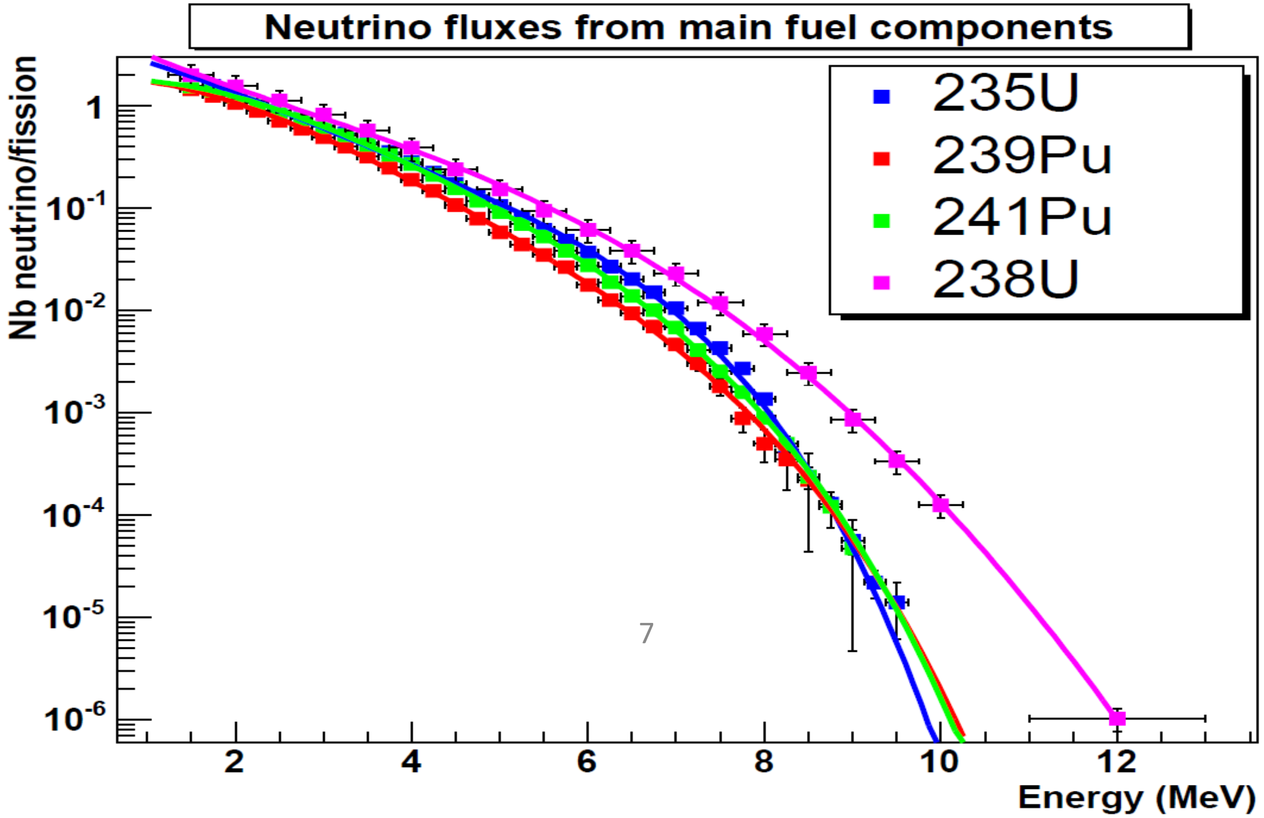
Because it significantly affects the supernova dynamics:

99% of energy of SN goes to ν!



Motivation of CEνNS experiments

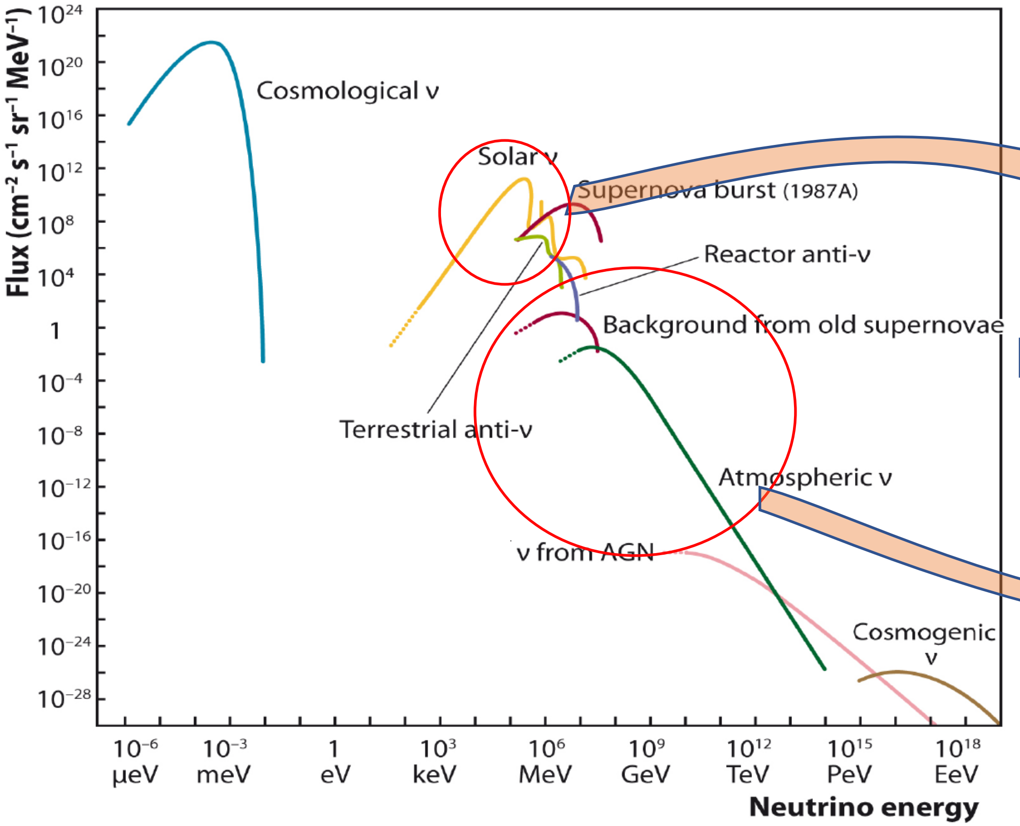
A new tool for monitoring of nuclear reactors



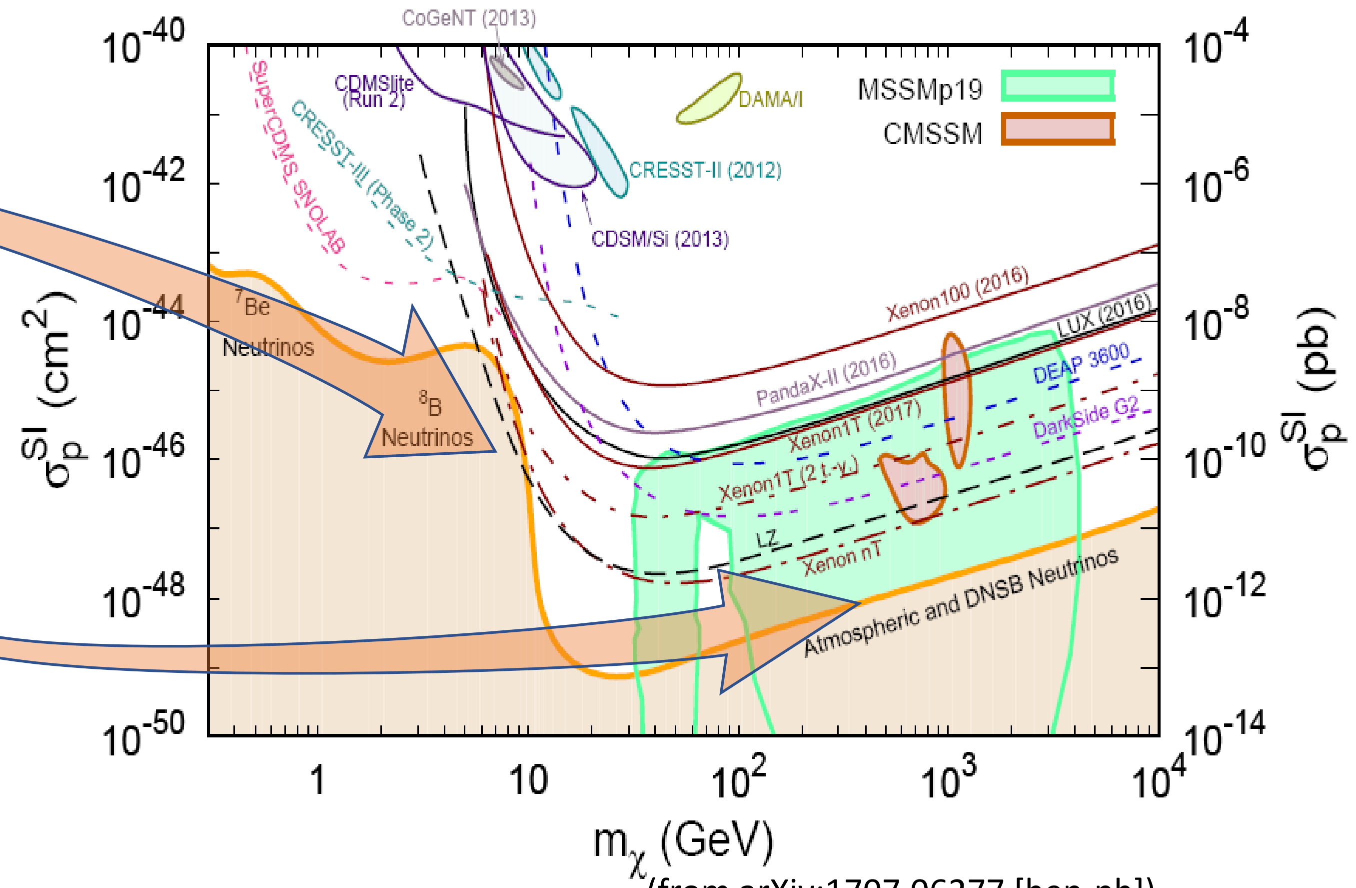
Motivation of CEvNS experiments

Knowledge on the precise CEvNS cross-section is very important for DM experiments:

CEvNS is an irreducible background floor for them



from arXiv:1207.4952v1 [astro-ph.IM]



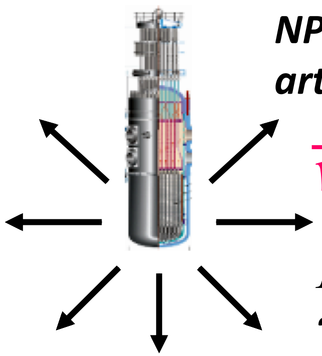
(from arXiv:1707.06277 [hep-ph])

PandaX-4T: arXiv:2407.10892 [hep-ex]

XENONnT: arXiv:2408.02877 [nucl-ex]

Talk by R. Calabrese, parallel section today

ν sources for CEνNS detection

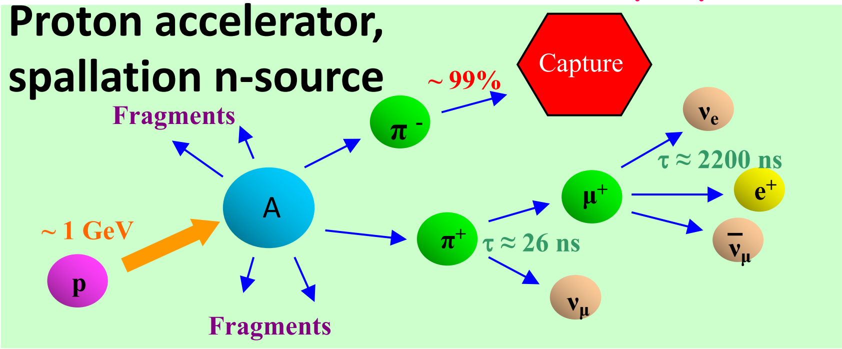


NPP reactor – is the most intense artificial source of $\bar{\nu}_e$

$\bar{\nu}_e$ ~ $6 \cdot 10^{20}$ c^{-1} for 3 GW

F_ν *@20 m*
~ $1.2 \cdot 10^{13}$ $cm^{-2}s^{-1}$

πDAR - pion Decay At Rest - $\nu_\mu, \nu_\mu, \bar{\nu}_e$



F_ν is by 10^6 lower, but σ is by 10^2 higher

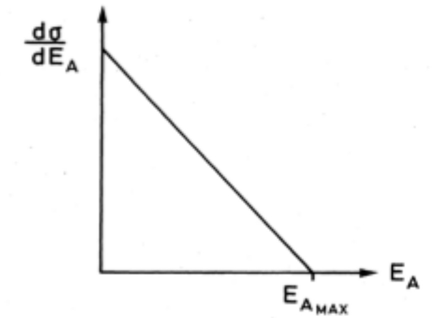
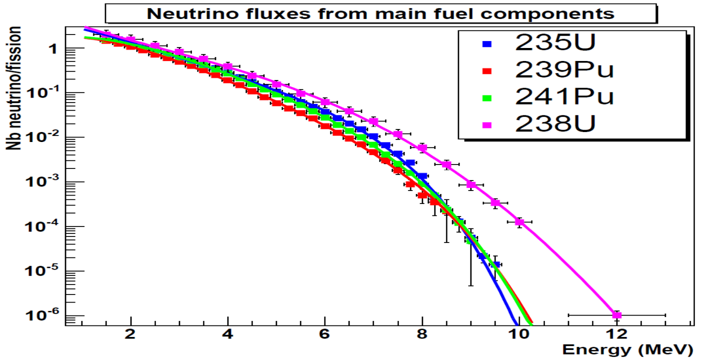
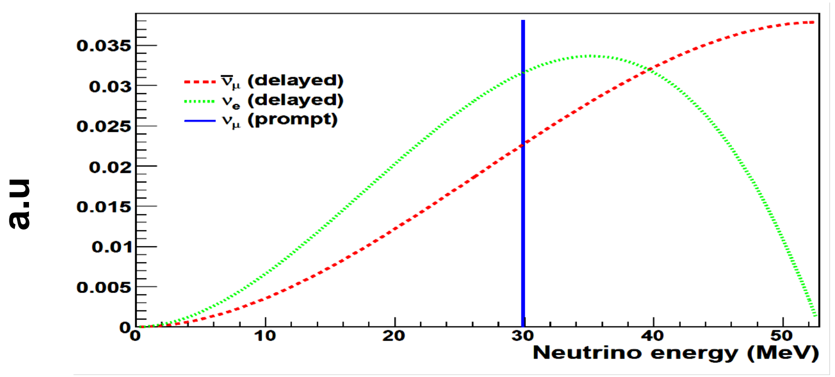
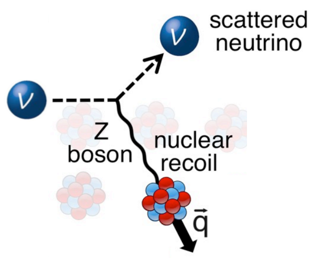


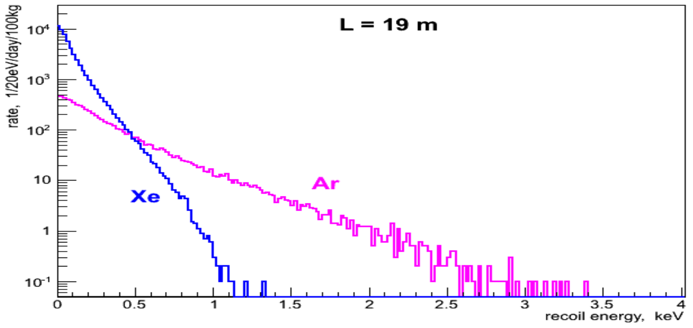
FIG. 1. Recoil-energy spectrum of the struck nucleus A in elastic neutrino scattering.



ν energy spectra

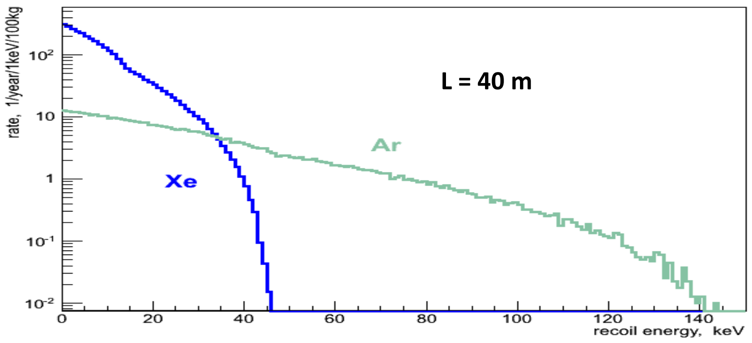






Nucl. recoil energy spectra

(Xe and Ar)

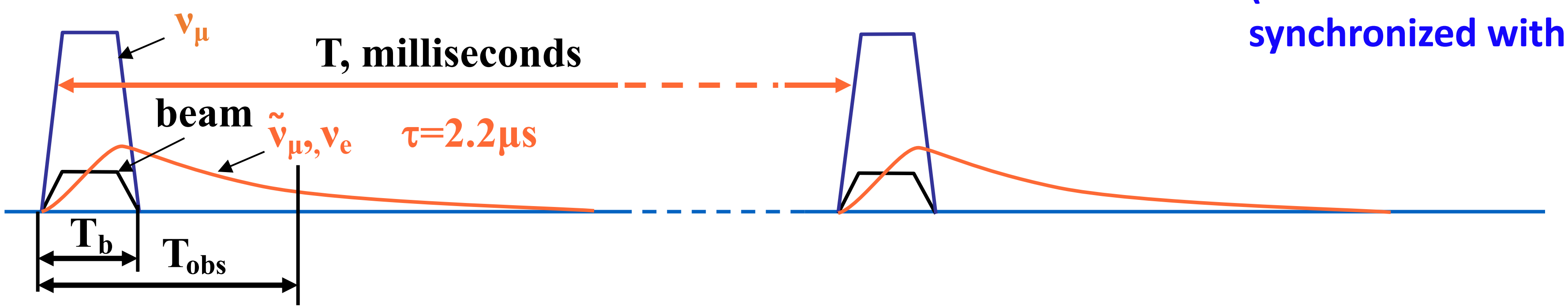


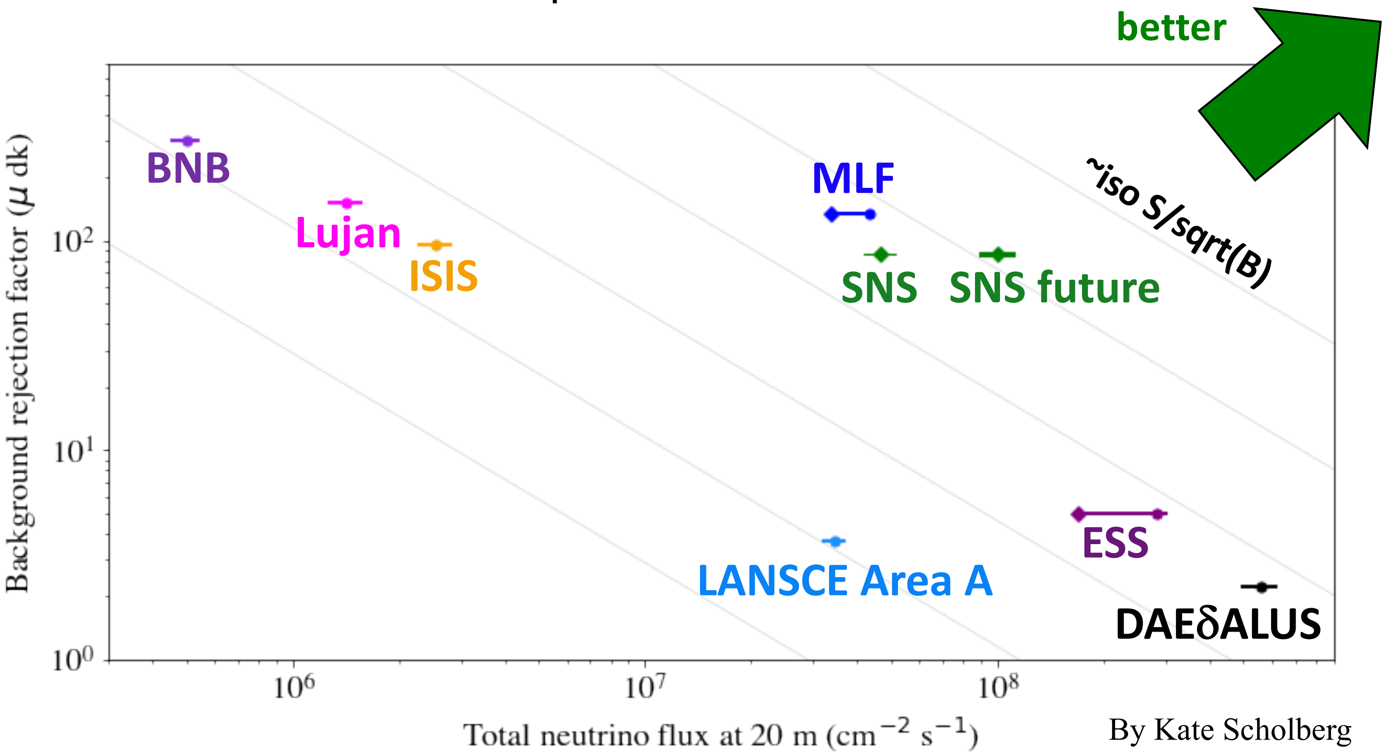
Accelerator - π Decay At Rest source

Pulsed beam of an accelerator is an essential factor of background reduction (by 1/Duty factor)!

Duty factor = $T_{obs}/T \sim 10^{-1} \div 10^{-5}$

(since measurements are synchronized with beam)





Lujan	US (LANL)
ISIS	UK (RAL)
BNB	US (FNAL)
SNS	US (ORNL)
MLF	Japan (J-PARC)
LANSCE Area A	US (LANL)
ESS	Sweden (planned)
DAEδALUS	US (planned)

How to detect CEvNS? History

The 1-st proposal of experiment on CEvNS detection:

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

In 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky

Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany

(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

Idea:

- Micron size metastable superconductive granules in a colloidal system placed in magnetic field
- The temperature is tuned so that some granules loose conductivity when the very small energy deposition happens in the detector
- This results to the measurable change of the magnetic field

The idea has never been realized, but stimulated DM detectors development

"The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light …"

"The recoil energy which must be detected is very small ($10 – 10^3$ eV), however."

"Various applications and tests are discussed, including spallation sources, reactors, supernova and terrestrial neutrinos."

In 1985

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

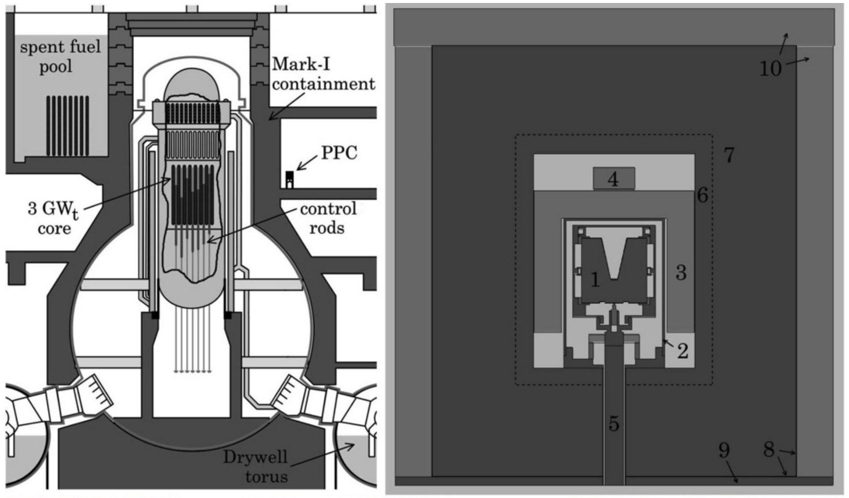
"We consider that the neutral-current detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos".

List of experiments on CEvNS detection

	Experiment	Mass, kg	Technology	Location	ν source
	CoGeNT	**0.5**	HPGe PPC	USA, San Onofre	Reactor
	TEXONO	**1.0**	HPGe PPC	Taiwan, Kuo-Sheng	Reactor
	RECODE	**1-2, 10**	HPGe PPC	China, Sanmen NPP	Reactor
✓	**Dresden-II**	**3.0**	HPGe PPC	USA, Dresden NPP	Reactor
✓	**CONUS** **CONUS+**	**4.0**	HPGe PPC	Germany, Brokdorf Switzerland, Leibstadt NPP	Reactor
✓	**νGEN**	**1.4**	HPGe PPC	Russia, Kalinin NPP	Reactor
✓	**CONNIE**	**0.04**	Si CCDs	Brazil, Angra dos Reis	Reactor
	MINER	**10**	Ge/Si bolometers	USA, TRIGA	Reactor
	ν-cleus	**0.01**	$CaWO_4$, Al_2O_3 bolometers	France, Chooz NPP	Reactor
	Ricochet	**1/0.3**	Ge, Zn bolometers	France, ILL-H7	Reactor
	NEON	**13.3**	Scintillator NaI	South Korea, Hanbit	Reactor
✓	**RED-100**	**100**	LXe/LAr two-phase	Russia, Kalinin NPP	Reactor
	RELICS	**50**	LXe two-phase	China, Sanmen NPP	Reactor
✓	**COHERENT**		CsI, Ar, Ge, NaI	USA, SNS	πDAR
	CCM	**10000**	LAr	USA, Lujan	πDAR

Most of them are reactor based

Dresden-II (NCC-1701) @Dresden NPP USA



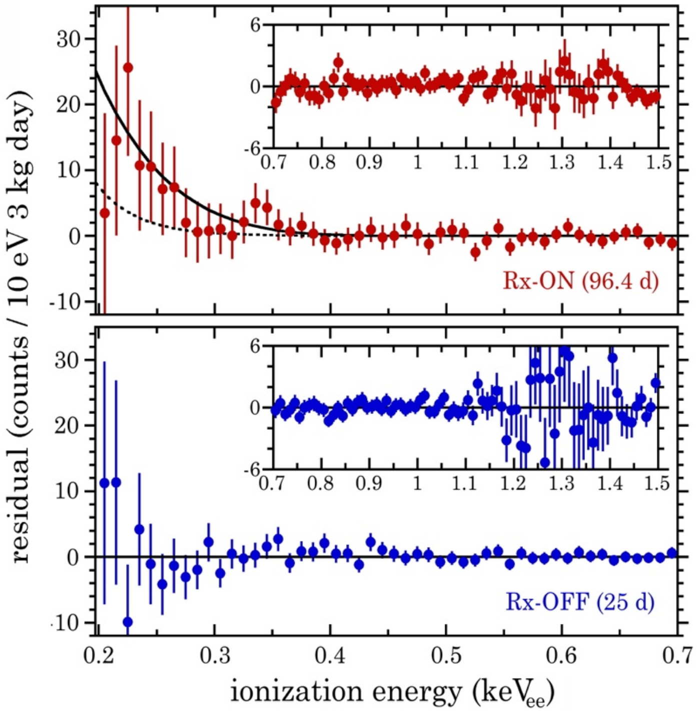
Very close to the reactor core:
10.39 m center-to-center

⬇

Very high $\overline{\nu}_e$ flux: $4.8\times10^{13}\ \overline{\nu}_e/cm^2s$
But, practically no overburden

p-PC Ge 2.9 kg, 200 eVee threshold

Claims observation of CEvNS (consistent with SM prediction)!
arXiv:2202.09672
Phys. Rev. Lett. **129** (2022), 211802



Residual betw. the data and bckg model

However, there is a criticism from the CEvNS community:

see Enectali Figueroa-Feliciano talk @M7, 22.03.2023:

- Claimed about strong preference ($p<1.2\cdot10^{-3}$) for the presence of CEvNS.
- Similar to nuGeN antineutrino flux from reactor ($4.8\ 10^{13}$ ν/cm2/sec)
- Sideway location gives almost no overburden (cosmogenic background).
- Almost no shielding against fast neutrons.
- Different shielding during reactor ON and OFF
- Big difference in background levels during reactor ON and OFF
- Moderate energy resolution > 160 eV (FWHM) (in nuGeN – 101.6(5) eV)

- **and measured QF is by >2 higher! arXiv:2102.10089 and see below**

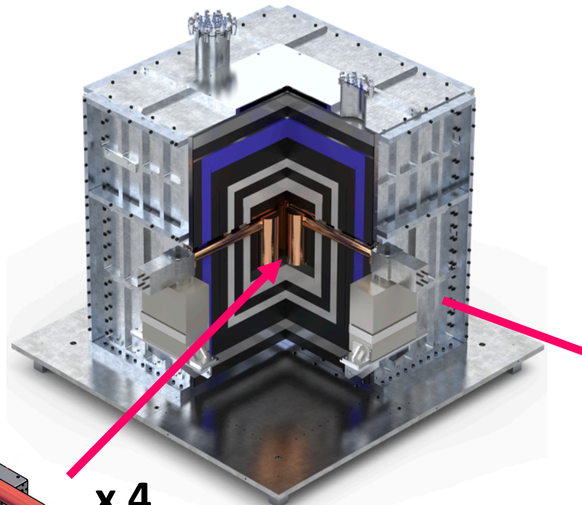
However, this result is in tension with the results of two similar experiments CONUS and ν GEN

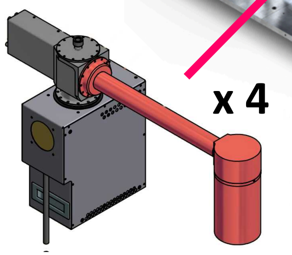
CONUS

Max-Planck-Institut für Kernphysik

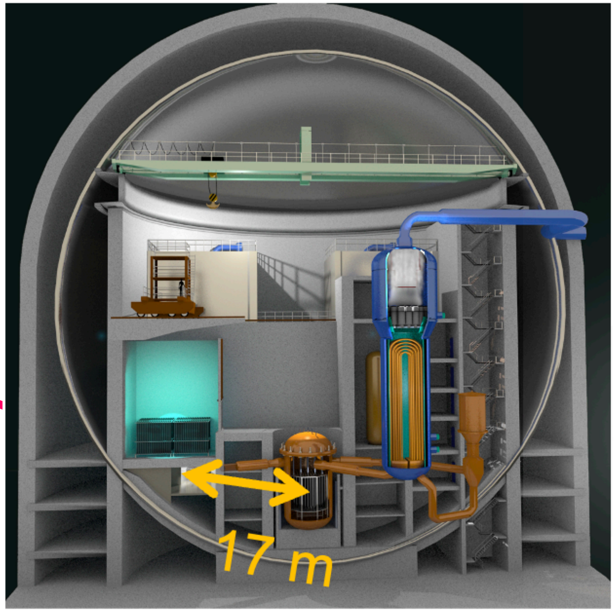
NPP Brokdorf , Germany

3.9 GW reactor





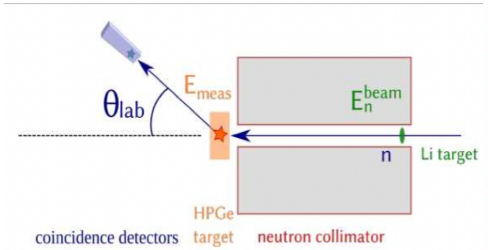
Borated Polyethylene
25 cm radiopure lead
Active μ-veto



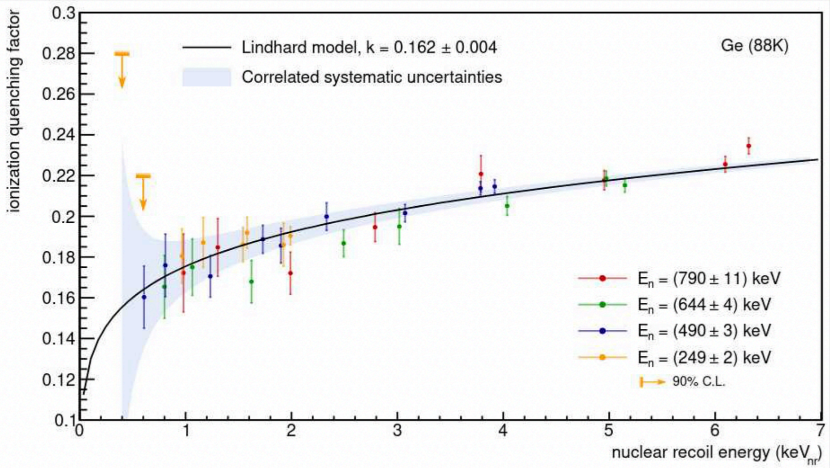
5 years of successful operation
4 x 1 kg Ge detectors @17 m
Φ=2.3 x 10^{13} ν/cm^2/s
Energy threshold ~200 eV$_{ee}$
Ultra-low bckg in ROI ~ 10 cpd/kg

From W. Maneschg talk @M7, 22.03.2023

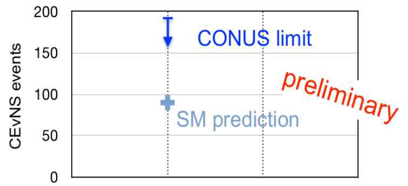
Careful QF (k) measurements



In ROI k=0.162+-0.004 (stat.+syst.)



- so far, statistical likelihood ratio test
- all Conus detectors do not find a signal
- combined limit (90% C.L.): factor ~2 above predicted CEvNS based on Lindhard quenching with k=0.162
- further slight improvements expected (PSD, additional statistics,…)



Janina Hakenmüller talk @M7, 12.06.24; arXiv:2401.07684

Factor of 2 > SM, 90% CF

Next phase - CONUS+ @ Leibstadt NPP in Switzerland
Taking data @ new place now

Comparison of Dresden-II and CONUS QF measurements

Dresden-II

Phys. Rev. D 103, 122003 (2021)

$^{72}Ge(n;\gamma)^{73}Ge$ => NR from γ emission

n – monoline 24keV from iron filter

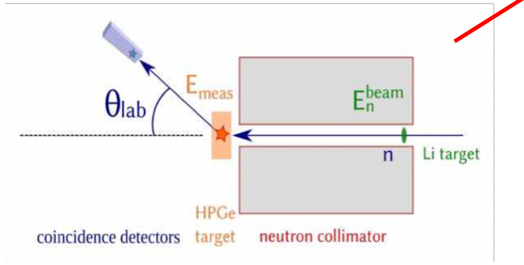
TUNL

https://hdl.handle.net/10161/25153

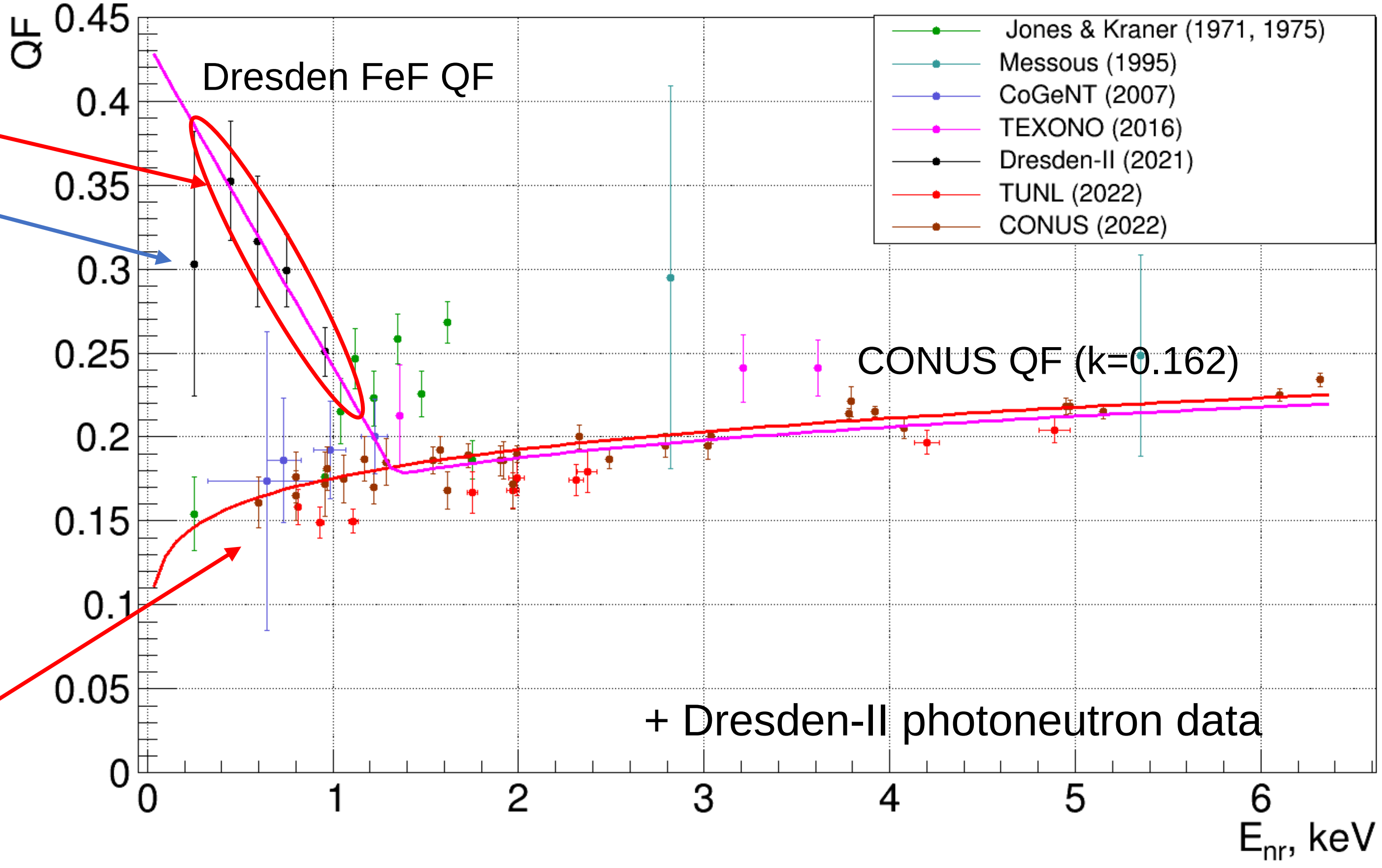
CONUS

Eur. Phys. J. C (2022) 82:815

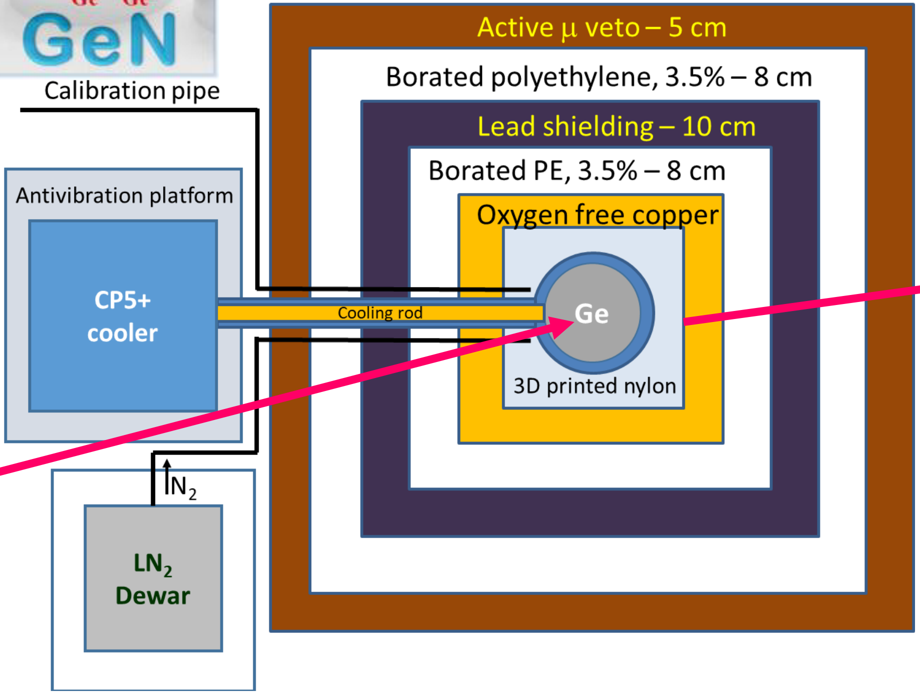
All these data – by selection of scatter angle of n



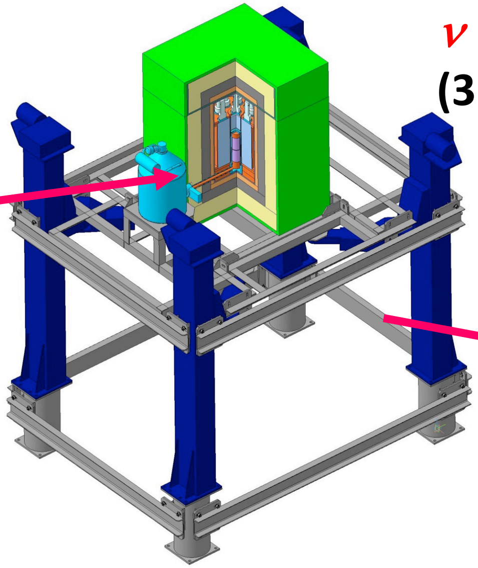
Comparison by vGen



ν GEN



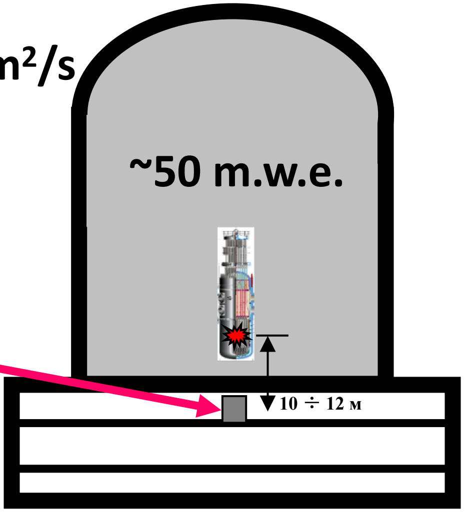
p-PC Ge 1.4 kg



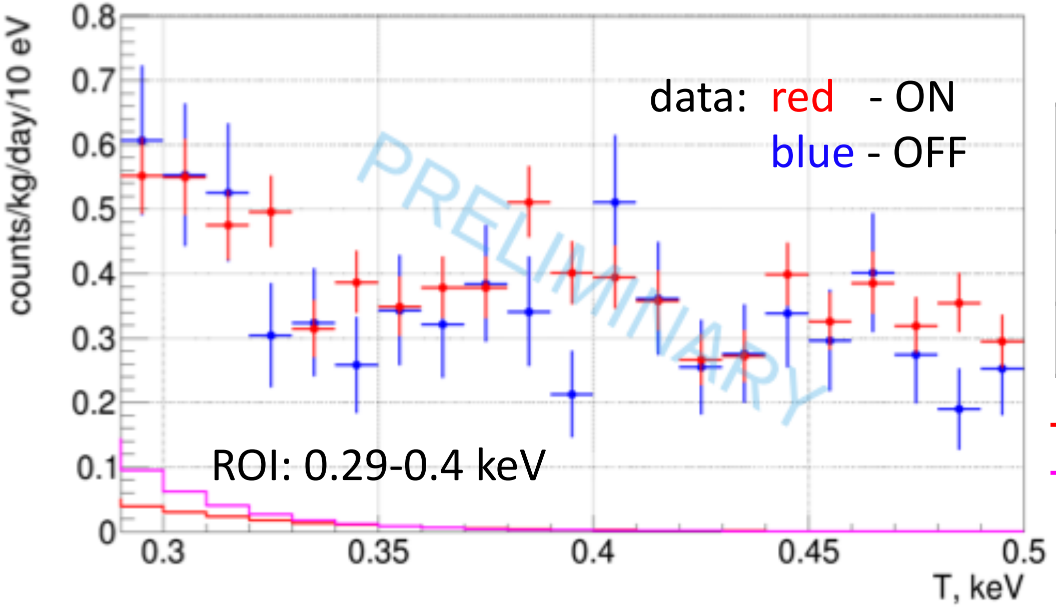
ν flux:

(3.6-4.4) 10^{13} ν/cm²/s

10 ÷ 12 m



•*Phys.Rev.D* 106 (2022) 5, L051101



from A.Konovalov talk @M7 12.06.2024

QF	Prediction, ev./kg/day	Sensitivity, ×SM	68% expectation for a 90% C.L. limit, ×SM
CONUS	0.159	4.1	2.3-6.0
Dresden	0.278	2.6	1.6-3.6

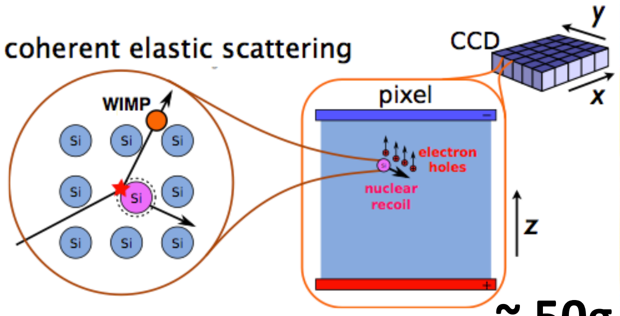
CEvNS prediction with CONUS QF

CEvNS prediction with Dresden OF

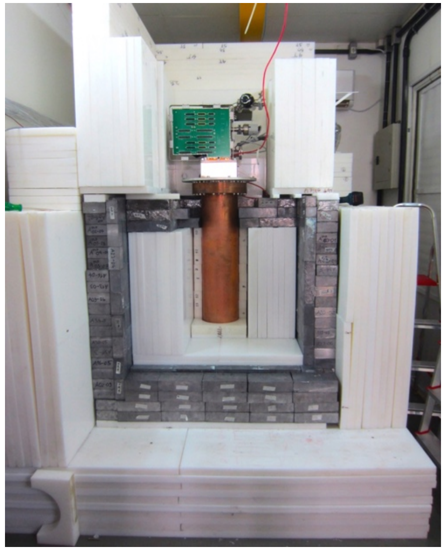
More details in A. Konovalov talk, this section

CONNIE (Coherent Neutrino Nucleus Interaction Experiment)

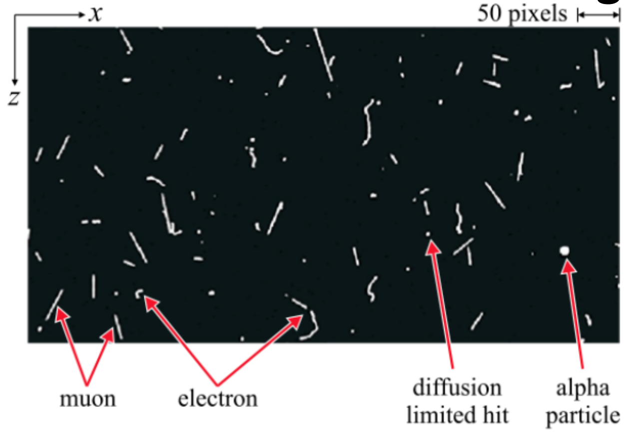
Si CCDs



~ 50g



Angra dos Reis NPP, Brazil



Rejection of ER interactions
and acception of only point-like NR events
Threshold ~ 50eV

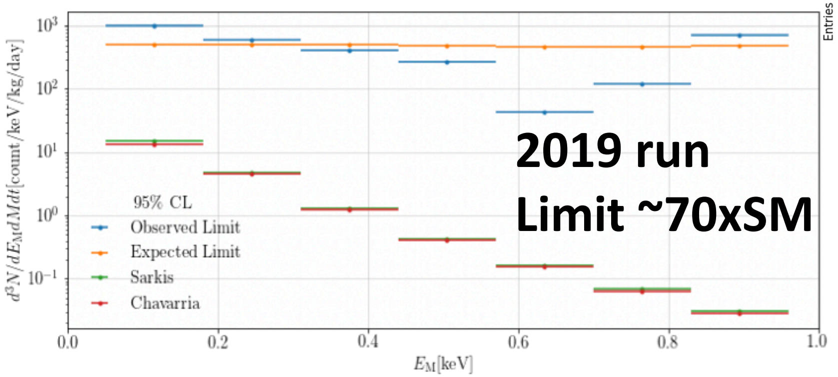
Now testing the new technology – Skipper CCD

Allows to improve s/n ratio by multiple measurement (>1000 times!) of each cell charge

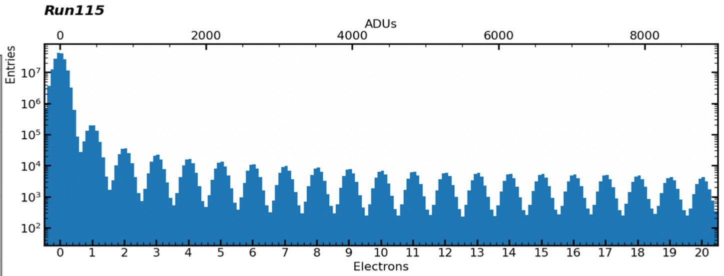
=> allows SE counting arXiv:2208.05434

Threshold => ~ 20 eV

arXiv:1608.01565, 2110.13620

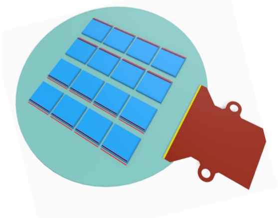


2019 run
Limit ~70xSM

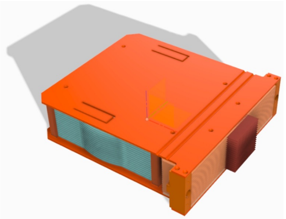


Now, only 0.5 g! Plans to install:

Multi-Chip Module
(16 CCDs → 8 g)



Super Module
(16 MCMs → 100 g)



Two-phase detectors

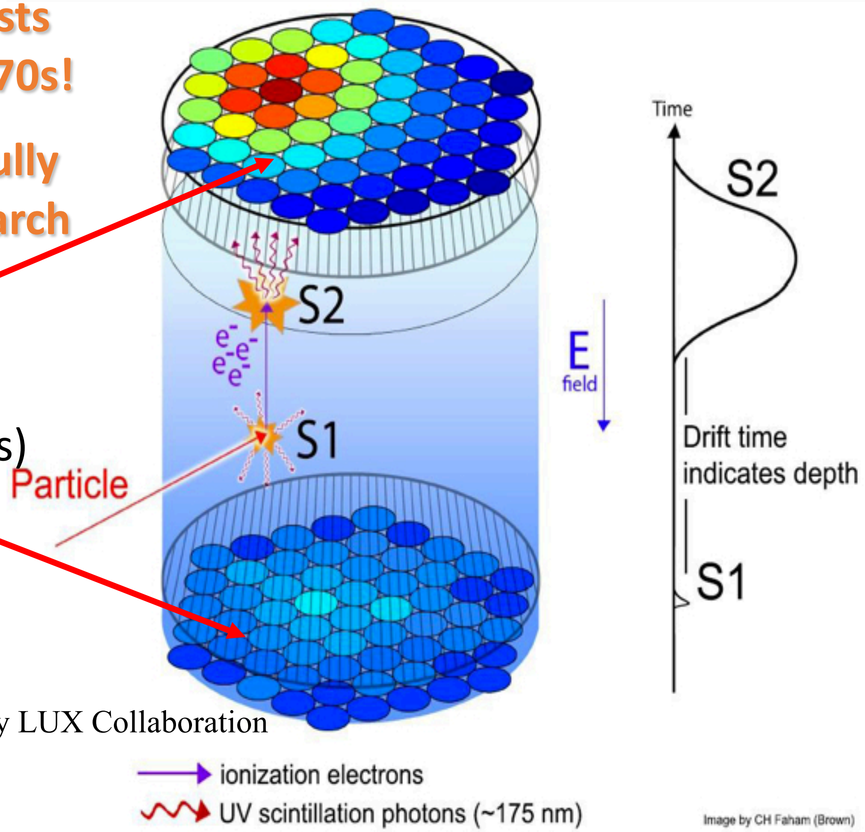
Two-phase method was proposed by Russian scientists in MEPhI in 1970s!

Later, successfully used in DM search

Emission two-phase detector

Photodetectors

(photomultipliers)



Picture by LUX Collaboration

The produced charge is extracted from the liquid to the gas phase

A two-phase method combines the advantages of gas detectors: the possibility of proportional or EL amplification, 3D positioning, SE counting, with the possibility to have the large mass (in the liquid phase)!

The progress in setting limits on SI WIMP-proton cross-section RAPIDLY increased with the use of two-phase detectors

The 1-st proposal for CEvNS detection was by C.Hagmann & A.Bernstein (LAr):

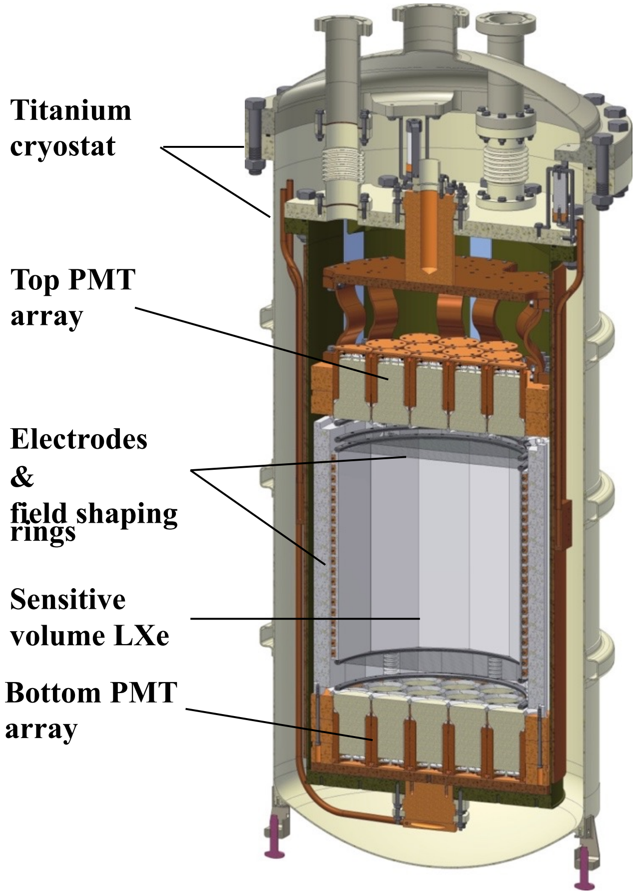
IEEE Transactions on Nucl. Science V.51 (2004), no.5, p2151

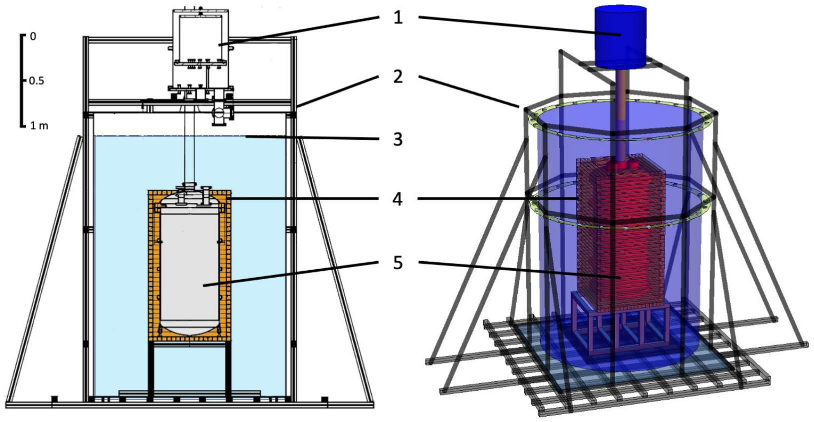
RED-100

@ Kalinin NPP, Russia

19 m from the core, ~50 mwe
ν flux: 1.35 10^{13} ν/cm²/s

- 26 PMTs Hamamatsu R11410-20 (19 in top PMT array, 7 in bottom PMT array)
- Contains ~200 kg of **LXe** or ~90 kg of **LAr** (~ 100 and ~50 kg in FV)





Design of the RED 100 passive shielding. 1 – LN2 tank, 2 – support frame, 3 – water tank, 4 – Cu shielding, 5 – Ti cryostat of the RED-100

Data taking run with LXe target:
mid Jan 2022–beg Mar 2022

342 kg·days ON

115 kg·days OFF

2022 JINST 17 T11011 – technical description

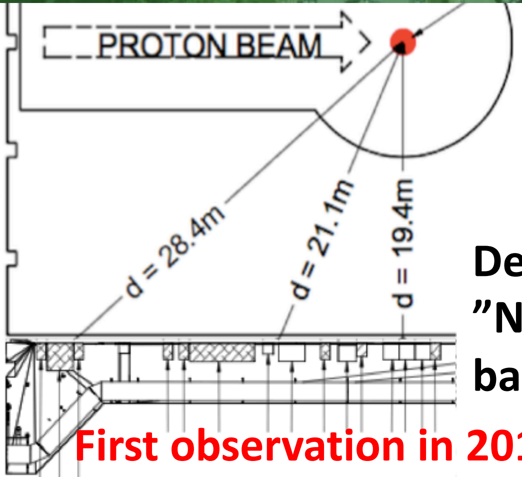
Energy threshold was set at 4 SE – corresponds to E_{NR} ~ 1 keV or E_{ν} ~ 8 MeV**!**
because of the very high rate (~30 kHz) of SE events – tails from muons

Current status: **lab tests with LAr target** - 3x larger signal, but ^{39}Ar bckg

More details in O. Rasuvaeva talk, this section

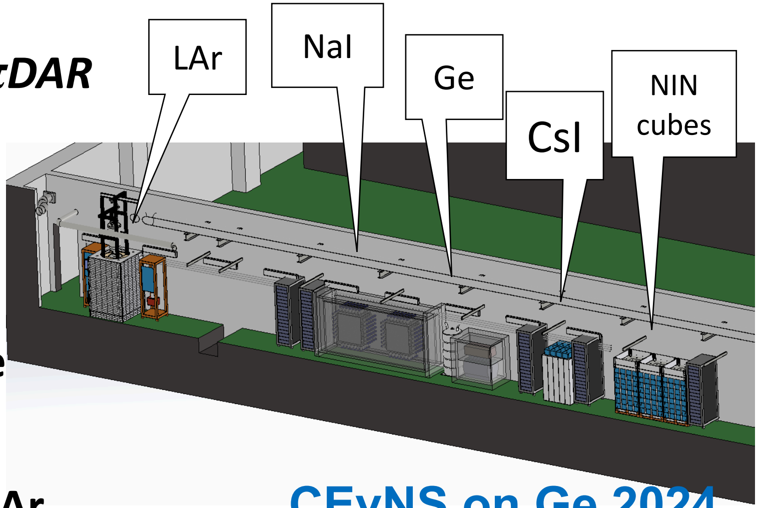
COHERENT – multidetector experiment with different targets

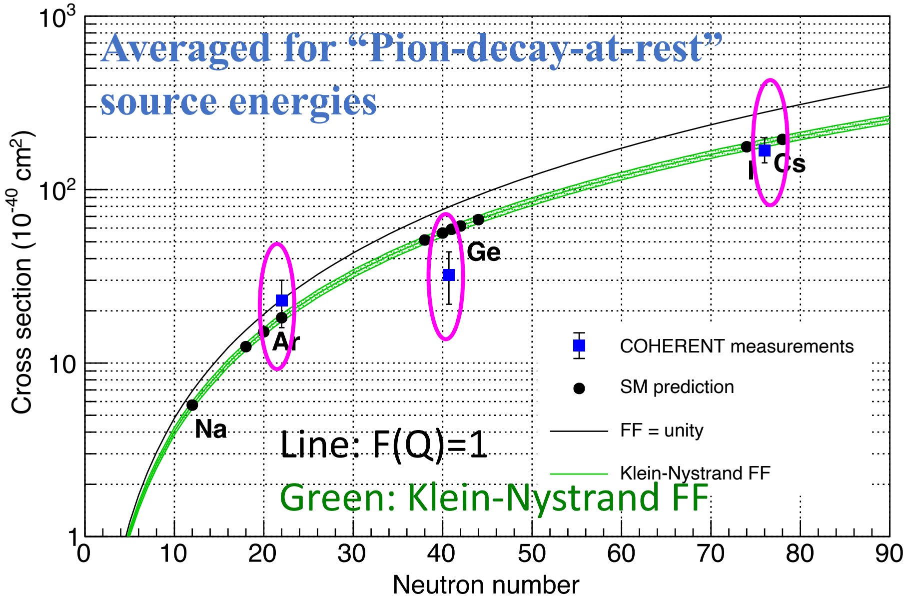
Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target



- *πDAR*

Detectors in ”Neutrino alley”, basement, 8 mwe





COHERENT measured CEvNS cross-sections for Ar, Ge, Cs&I.

First observation in 2017 with CsI detector

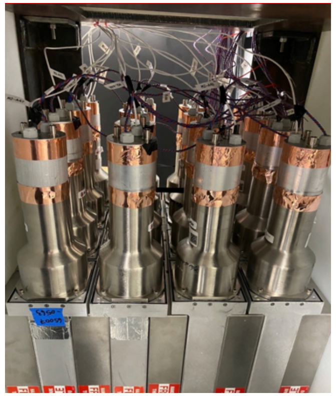
***CEvNS* on CsI, full statistics**
*PRL **129** (2022) 081801*

***CEvNS* on Ar**
*PRL **126** (2021) 012002*

CEvNS on Ge 2024
arXiv:2406.13806v1 [hep-ex]

Coming soon:

NaI detector 2425 kg of NaI crystals



Coming soon:

CENNS-750 (750-kg LAr) is under construction 600 kg FV

Planning:

Cryo-CsI (undoped with SiPM readout) PE yield – up to 50 PE/keV

More details in A. Kumpan talk, this section

CONCLUSION

- CEvNS is a channel of the low-energy neutrino interaction with matter with the highest probability (by ~ 10^2 – 10^3 higher than for other processes)
- More than 40 y passed from the prediction of CEvNS to its experimental confirmation
- Many experiments aimed on CEvNS observation and study are ongoing
- For the moment, CEvNS is reliably detected by only COHERENT at SNS for Ar, Ge and Cs&I
- The 1-st results on CEvNS from neutrino "fog" appeared
- Sensitivity of reactor experiments on CEvNS detection is approaching the SM prediction
- More results are expected very soon